

# COMBUSTION INSTABILITY ANALYSIS AND THE EFFECTS OF DROP SIZE ON ACOUSTIC DRIVING ROCKET FLOW

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## ABSTRACT

High frequency combustion instability, the most destructive kind, is generally solved on a per engine basis. The instability often is the result of compounding acoustic oscillations, usually from the propellant combustion itself. To counteract the instability the chamber geometry can be changed and/or the method of propellant injection can be altered. This experiment will alter the chamber dimensions slightly; using a cylindrical shape of constant diameter and the length will be varied from six to twelve inches in three-inch increments. The main flowfield will be the products of a high O/F hydrogen/oxygen flow. The liquid fuel will be injected into this flowfield using a modulated injector. It will allow for varied droplet size, feed rate, spray pattern, and location for the mixture within the chamber. The response will be deduced from the chamber pressure oscillations.

## INTRODUCTION

The excitation of acoustic oscillations in combustion chambers is well known as an undesirable phenomenon that impedes efficient burning and promotes structural stresses that can lead to engine and combustor failure<sup>1</sup>. Understanding, classifying and ultimately controlling thermoacoustic excitation is an important goal and is of interest to engineers and theoreticians alike. However, accurate predictions for the onset of acoustic-combustor instabilities are difficult to make, and models created to account for these difficulties make use of parameters that are specific for that combustor in question and whose mathematical origins are usually puzzling.

Combustion instability results from the coupling between the combustion and the fluid dynamics of the system. Through this coupling, oscillatory energy is supplied by the combustion to sustain the oscillations. Only if the damping processes present in the system are sufficiently large to dissipate the oscillatory energy more rapidly than it is supplied, the oscillation will decay. Thus, instabilities may be prevented by either increasing the damping or by decreasing the coupling with the driving forces. Combustion instability is characterized by chamber pressure oscillations, although the frequency and amplitude of these oscillations and their external manifestations normally vary with the type of instability. Severe oscillations are typically characterized by the presence of well-developed acoustic standing waves. These oscillations can produce severe fluctuations, which are dangerous since they can lead to excessive vibrations resulting in mechanical failures, high levels of acoustic noise, high burn and heat transfer rates, and possible component melting<sup>2</sup>. Decreased performance, uncontrolled impulse, variation in thrust vector, and oscillatory propellant flow rates are also effects of the instability. Therefore, combustion instability has become a key issue in modern combustion.

One of the most famous engines, the F-1 engine, was plagued with instabilities. The instabilities of the engine were serious for more than seven years during the development of the engine<sup>3</sup>. Twenty of the forty-four tests of the first F-1 engine experienced combustion instabilities with peak amplitudes either greater than or comparable to the average pressure. The pressure oscillations caused erosions and

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burning of the injector face, which was indicative of the presence of large radial and tangential motion. In order to evade the instability problems, a program called Project First was created to develop a stable F-1 engine. Project First lasted for four years (1962-1965). During this time, the engine was subjected to more than 2000 full-scale tests, probably the most concentrated and expensive program ever devoted primarily to solving problems of combustion instabilities<sup>3</sup>.

The most suitable method of detection and study of the instability is the measurement of the chamber pressure. Pressure measurements made in the propellant feed system show similar oscillations and in some cases measurements made here may be greater than that measured in the combustion chamber<sup>4</sup>. Physical manifestations are often shown by means of vibration measurements, which are sometimes referred to as "rough combustion"<sup>4</sup>. Vibration measurements often do not correlate well with corresponding chamber pressure measurements, but similarities in frequency or amplitude are common. The heat transfer rates can be examined by burying thermocouples in the chamber wall.

Instabilities are classified by their effects, the coupling mechanism, and by the devices used to eliminate them. Low frequency also referred to as "chug" or "putt-putt" is encountered when the frequency is less than several hundred hertz. The wavelength is usually much larger than the characteristic dimensions of either the chamber or feed system. In some cases, the wave motion in the propellant lines usually will begin with low amplitude, sinusoidal shape, and will grow in a linear fashion to higher amplitude. Low frequency instabilities can be simulated analytically by a lumped element method. The combustion is represented as a simple, constant time delay and the propellant feed system is usually neglected, although the feed system and capacitance may become important in the analysis. Low frequency instabilities may be eliminated by increasing the pressure drop in the injector, lengthening the L/D in the injector or feed system, or by decreasing the chamber volume<sup>4</sup>. Low frequency instabilities are subacoustic in frequency and are the easiest instabilities to manage from both an analytical and experimental perspective.

High frequency, resonant combustion is the most destructive type of instability. It is also referred to as "screaming." The feed system is usually unimportant in the analysis. An oscillatory source of energy is required to sustain the instability. Each oscillatory wave affects the propellant combustion strongly enough so that the sustaining energy is added directly to that wave. When this happens, the instability grows until equilibrium is reached. For stable engines, equilibrium will occur at zero amplitude while for unstable engines, this occurs at a finite value<sup>4</sup>. For high frequency instabilities, energy must come from propellant combustion and is usually only weakly dependent upon the feed system. These kinds of instabilities can be eliminated by making changes in the propellant spray combustion field or in the pressure wave character (wave shape alterations can be accomplished through changes in geometry) so that the combustion response to the wave motion releases less oscillatory energy than required for sustaining the oscillations<sup>5</sup>. Other elimination methods include changes in the dynamic energy loss or damping so that they exceed the energy gains from the combustion response<sup>4</sup>.

Analyzing combustion instabilities can be very complicated with many degrees of freedom that cannot be easily separated for mathematical analysis. The condition under which a combustion system becomes unstable has been expressed in terms of the Rayleigh criterion<sup>6</sup>. The Rayleigh criterion states that "if heat be given to the air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction, the vibration is encouraged<sup>5</sup>." In other words, heat addition tends most strongly to drive acoustic waves if the energy is added in the region of space where the oscillating pressure reaches the greatest amplitude and is in phase<sup>3</sup>.

$$\int_0^{\tau} \int_0^v \dot{p}(x, t) \dot{q}(x, t) dv dt > \int_0^{\tau} \int_0^v \phi(x, t) dv dt \quad (1)$$

where  $\dot{p}$  and  $\dot{q}$  are the perturbation in pressure and the heat release, respectively,  $\tau$ ,  $v$ , and  $\phi$  are the period of oscillation, the control volume (the combustor volume), and the wave energy dissipation. An acoustic mode will be rendered unstable when the phase of the unsteady burning of the chamber coincides with the sound's pressure fluctuation.

The instability occurs when (1) is satisfied. Both sides of the inequality describe the total mechanical energy added to the oscillations by the heat addition process per cycle<sup>2</sup>. Usually, the acoustic dissipation in combustors can be assumed to be very small (RHS~ 0). The LHS of the inequality indicates that in order to satisfy the Rayleigh criterion, a specific relationship between  $\dot{p}$  and  $\dot{q}$  must exist<sup>5</sup>. From the Rayleigh condition, when  $\dot{p}$  and  $\dot{q}$  are out of phase, the effect will be a stabilizing one, and when they are in phase, the effect will be destabilizing. Since the integrals are spatial, both effects can occur in different locations of the combustor and at various times. The stability of the combustor is decided upon by the total net mechanical energy added to the combustor. Compressions in the acoustic field are assumed to be isentropic; therefore, the inequality can become valid also if the integral in the LHS involves the dynamics between the heat fluctuations and either of the variables including pressure, temperature, and density<sup>2</sup>.

The experiment to be conducted will validate a chamber acoustics model utilizing passive control elements and the effects on combustion response will be measured. The effects of drop size on acoustic driving in a rocket flow will also be measured. The drops will be injected into an oxygen rich combustion environment. The drop size will be modulated and the combustion response will be measured.

Rapid droplet vaporization is essential to efficient combustion. The combustion behavior of sprays is a statistical consequence of the vaporization behavior of its interacting individual droplets<sup>4</sup>. The vaporization rate depends on the atomization process, which determines the drop size. Other factors that could influence the stability of droplet combustion are the variation of pressure, temperature, and velocity in the chamber. The kinetic factors, such as, induction period, activation energy, and reaction mechanisms could also influence the stability of the rocket engine.

## EXPERIMENTAL DESIGN

### CHAMBER DESIGN

The diameter of the combustor is 2.125 in (5.4 cm). This diameter was chosen in order to accommodate other experiments that are being conducted at the University. The combustor is constructed from oxygen-free high conductivity copper (OFHC). This material was chosen because of its thermal conductivity. The outer diameter of five inches yields a factor of safety of approximately 3.5 at 2000 psi at room temperature. The factor of safety decreases to 3.0 at 400°F, the temperature at which the o-rings begin to melt. The lengths of the combustor will be varied in order to study the acoustic response of the chamber.

### FREQUENCY CALCULATIONS

The speed of sound and the chamber temperature were calculated with Thermodynamic Equilibrium Program (TEP™)<sup>7</sup> for various oxygen-to-fuel ratios as a function of a chamber pressure of 2000 psi (13788 KPa). Figure 1 shows the sonic velocity and temperature curves as a function of the oxygen-to-fuel ratio.

With this information, the longitudinal, first tangential, second tangential, and first radial frequencies were calculated as a function of the O/F ratio for varying chamber lengths of 6 in (15.24 cm), 9 in (22.86 cm), and 12 in (30.48 cm). The longitudinal frequency was approximated by equation (2)

$$f = \frac{\bar{c}}{2x_c} \quad (2)$$

where  $c$  is the speed of sound and  $x_c$  is the effective length of the chamber. The fluid velocity was neglected in this calculation. The first tangential, second tangential, and first radial frequencies were calculated from equation (3)

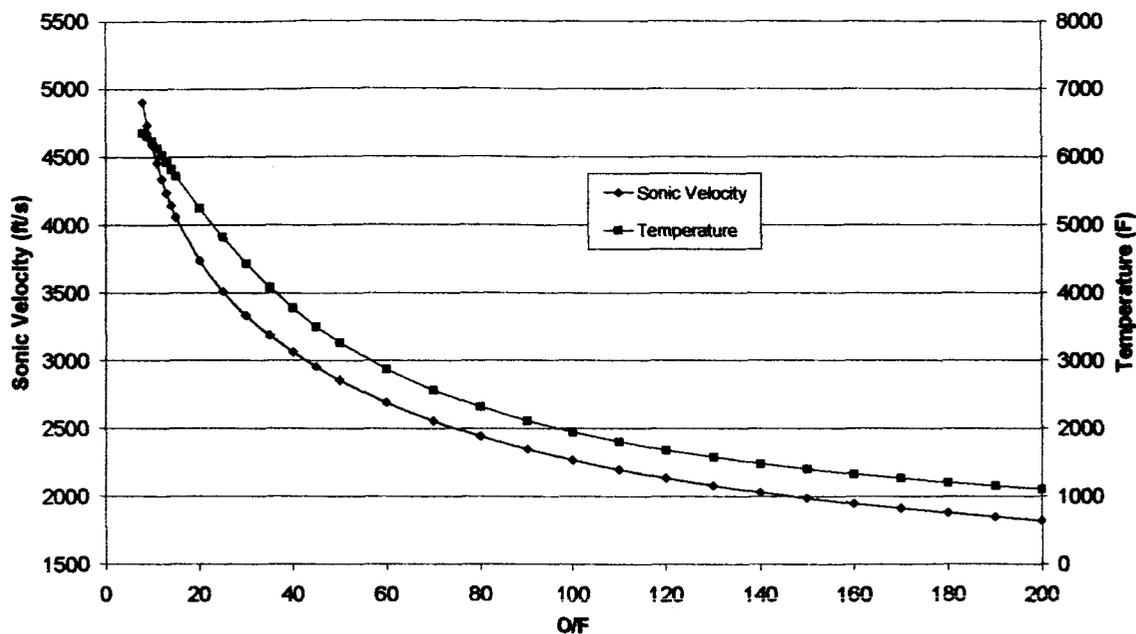


Fig. 1 Sonic velocity and temperature versus O/F for gaseous oxygen gaseous hydrogen at 2000 psi (13788 KPa).

$$f = \frac{S_{v\eta} \bar{a}_c}{2\pi r_c} \quad (3)$$

where the value of  $S_{v\eta}$  is dependent upon the character of the transverse mode,  $a_c$  is the speed of sound, and  $r_c$  is the radius of the chamber. The various frequencies calculated are given in figures 2 and 3. Figure 2 is the longitudinal frequency versus the O/F ratio for the chamber. Figure 3 is the tangential and radial frequency versus the O/F ratio.

### INJECTOR DESIGN

The injector design is incomplete at this point, but ideas are being explored. It is known that the steady-state gas dynamic flow pattern within a rocket thrust chamber is determined mainly by the injector design<sup>4</sup>. The most important quality of the injector is flexibility. The main injector will inject gaseous hydrogen and oxygen into a showerhead configuration to produce a uniform flow of hot gases. A high-frequency modulated-flow fuel injector developed by Fluid Jet Associates is being investigated to inject the liquid fuel. A piezoelectric actuator modulates the fuel flow and it also modulates the spatial distribution of the atomized fuel<sup>8</sup>. The fuel flow or the drop size can be modulated. The frequency of modulation will be varied and the effect on the chamber pressure oscillation will be measured. From these data, the combustion response will be deduced.

A Nanomiser liquid fuel atomizer is also being investigated. This fuel injector requires no atomizing gases to produce mono-dispersed spray, which allows control over the mean droplet diameter. These atomizers are capable of generating droplets from 100 micron down to sub-micron range<sup>9</sup>. Tests with this injector will most likely need to be bombed or the pressure perturbed in some other way in order to measure the response.

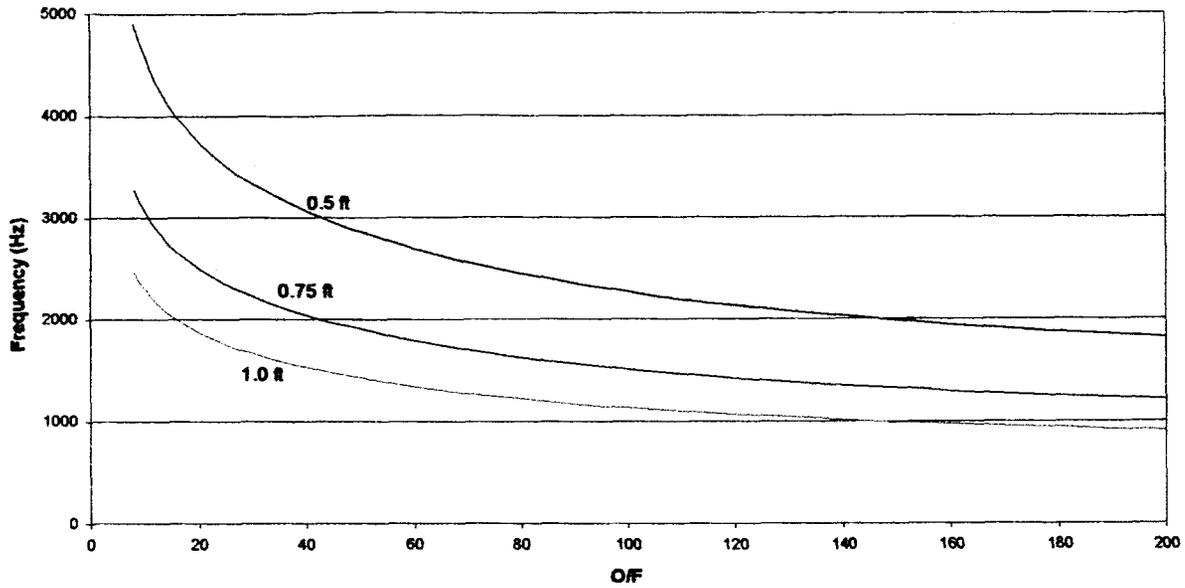


Fig. 2 Longitudinal frequency versus O/F as a function of length of the combustor for gaseous oxygen and gaseous hydrogen at 2000 psi (13788 KPa).

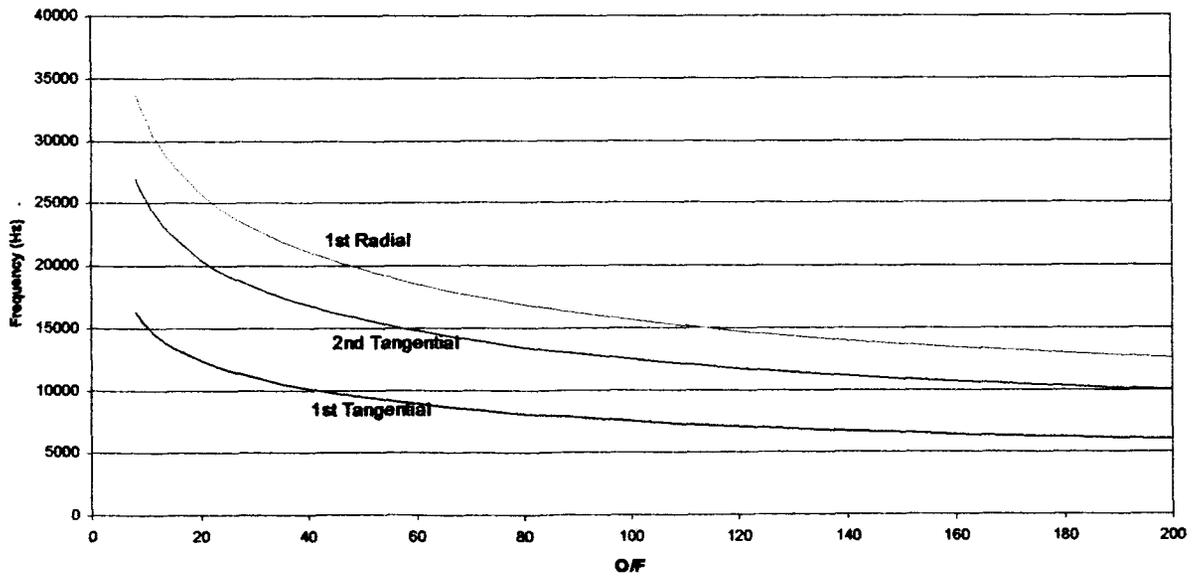


Fig. 3 Tangential and radial frequencies versus O/F for gaseous oxygen and gaseous hydrogen at 2000 psi (13788 KPa).

## SUMMARY AND CONCLUSIONS

Combustion instability results from the coupling between the combustion and the fluid dynamics of the system. Through this coupling, oscillatory energy is supplied by the combustion to sustain the oscillations. Combustion instability is characterized by chamber pressure oscillations, although the frequency and amplitude of these oscillations and their external manifestations normally vary with the type of instability. High frequency, resonant combustion is the most destructive type of instability.

The experiment to be conducted will validate fundamental data on coupling of instabilities with drop size. The combustion chamber will be circular with a diameter of 2.125 in (5.4 cm) with varying lengths of 6 in (15.24 cm), 9 in (22.86 cm), and 12 in (30.48 cm). The experimental apparatus is nearly complete and experiments will begin later this year.

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